Pyrotechnic Modeling for the NSI and Pin Puller

Joseph M. Powers[1] and Keith A. Gonthier[2]

Department of Aerospace and Mechanical Engineering

University of Notre Dame

Notre Dame, Indiana 46556-5637

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Houston, Texas 77058

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[1]Assistant Professor, 219-239-5978, powers@neumann.ame.nd.edu

[2]Graduate Assistant

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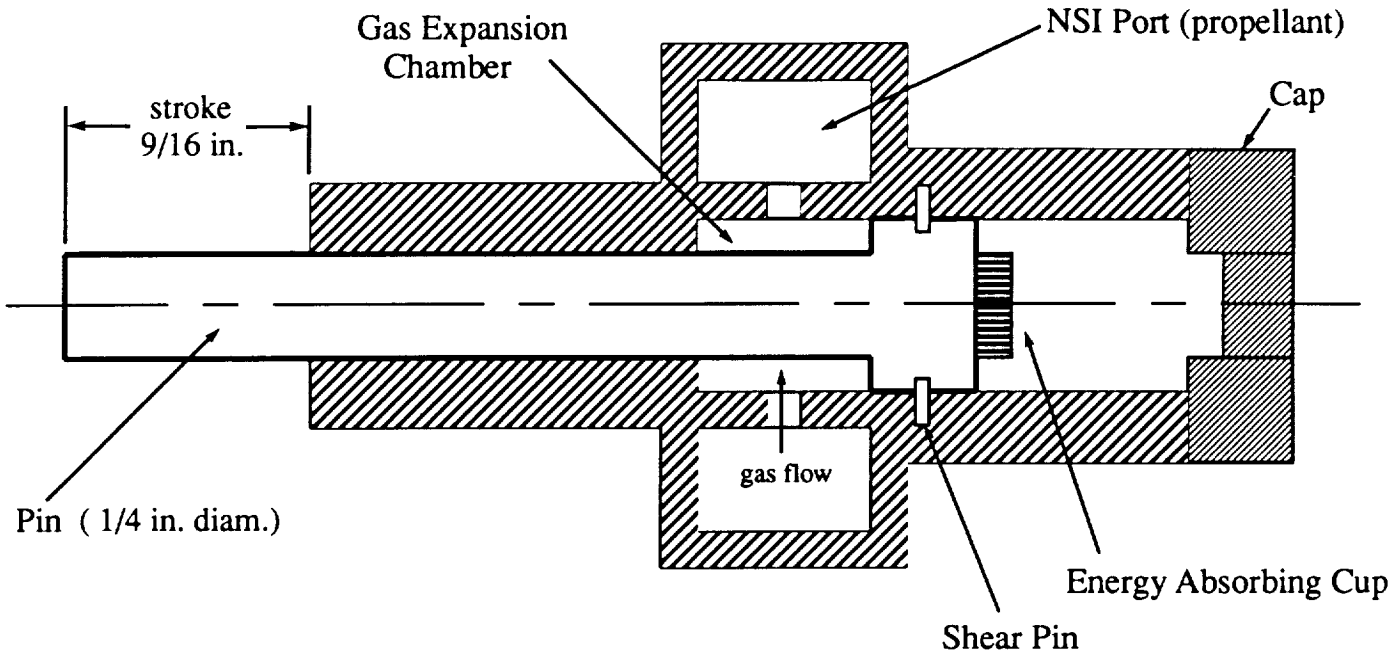
Discussions

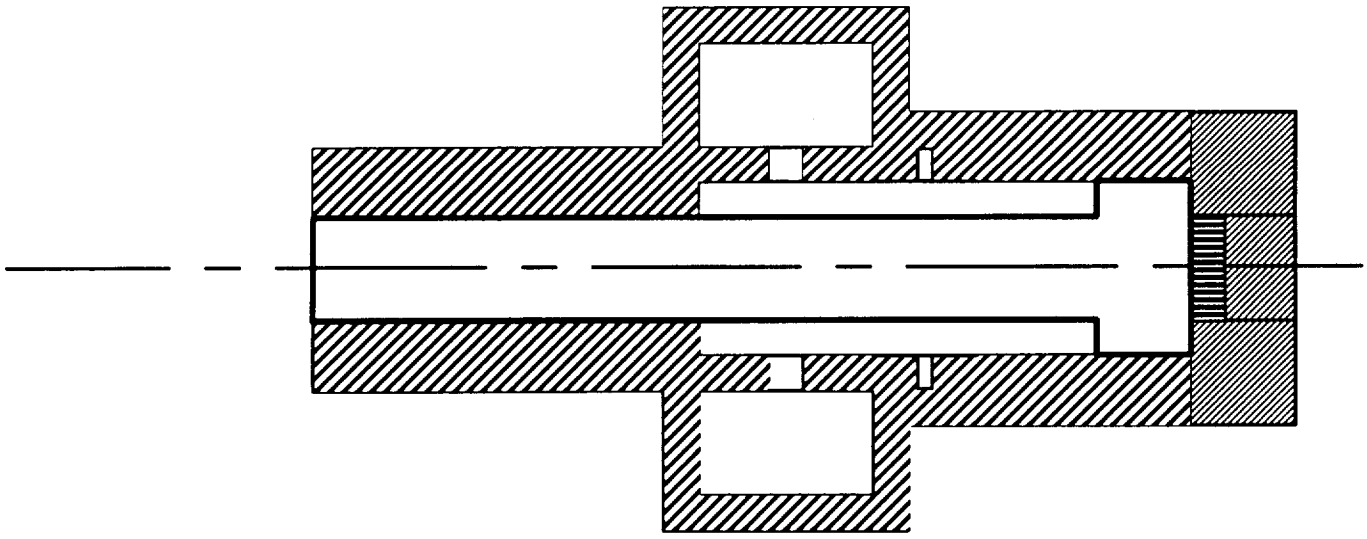
Prof. P. Barry Butler
University of Iowa

NSI Driven Pin Puller

(unretracted pin)



(retracted pin)



Review

Sources for guidance in model development:

- Pin-puller tests: Bement, Schimmel, et al.
- Pyrotechnics chemistry: McLain, Conklin
- NSI ignition study: Varghese
- Multiphase combustion: Baer, Nunziato, Krier, Powers, etc.
- Automobile airbags: Butler
- Solid propellants: Williams, Kuo, Strehlow, etc.
- Solid state combustion synthesis: Varma

Engineering Problems

- occurance of operational failures
- qualification only after many tests
- difficult to predict behavior of new formulations
- difficult to quantify effects of modifications
  - diffusive heat transfer
  - molecular heat transfer
  - pin puller geometry
  - friction
  - apparantly random sample behavior

Modeling Approaches

- Full Scale Models
  - time-dependent
  - three-dimensional spatial gradients
  - multiple species, multiple reactions
  - fully resolved chemical kinetics
  - compressiblity
  - turbulence
  - real gas effects
  - boundary layers
  - *essentially no detailed kinetic data available*
  - *more complex than justified by data*

- Empirical Models
  - experimentally-based correlations
  - reliable in limited ranges
  - somewhat inflexible
- Simple Models-*present approach*
  - analytically tractable
  - judgment required
  - simplicity at expense of loss of rigor
  - introduction of ad hoc assumptions
- Stochastic Models
  - estimates for uncertainty required
  - could be coupled with simple model

Assumptions for Simple Model

- no spatial variation
  - $t_{acoustic} \sim \frac{L}{c} \sim \frac{0.01m}{1000m/s} = 1 \times 10^{-5}s$
- constant density solid pyrotechnic
- constant surface area of pyrotechnic
- linear pyrotechnic burn rate known
- constant temperature wall
- simple convective heat transfer
  - $t_{conv} << t_{cond} \sim \frac{L^2}{\alpha} \sim \frac{(0.01m)^2}{0.001m^2/s} = 0.1s$
- simple radiative heat transfer
  - $t_{rad} \sim \frac{\rho_g c_{vg} L}{\sigma T^3} \sim \frac{1kg/m^3 1000J/(kgK)0.01m}{1\times10^{-7}J/(sm^2K^4)(1000K)^3} = 0.1s$

- negligible heat tranfer from gas to solid
- negligible wall friction and shear pin resistance
- non-negligible pin inertia
- multicomponent ideal gas behavior
- temperature dependent specific heat
- Gibbs free energy minimization
  - determines heat of reaction
  - determines mass fractions of gas products

Conservation Principles

for background see

Powers, Stewart, and Krier, "Theory of Two-Phase Detonation–Part I: Modeling, Part II: Structure," *Combustion and Flame*, V. 80, 1990.

$$
\begin{aligned}
\frac{d}{dt}\left[\rho_g V_g\right] &= \rho_s A r \\
\frac{d}{dt}\left[\rho_s V_s\right] &= -\rho_s A r \\
\frac{d}{dt}\left[\rho_g V_g e_g\right] &= \rho_s A r e_s + hA(T_w - T_g) \\
&\quad + \sigma A(\alpha T_w^4 - \epsilon T_g^4) - P_g \frac{dV}{dt} \\
\frac{d}{dt}\left[\rho_s V_s e_s\right] &= -\rho_s A r e_s \\
m_p \frac{d^2}{dt^2}\left[\frac{V}{A}\right] &= P_g A
\end{aligned}
$$

Constitutive Relations

$$
\begin{aligned}
r &= a + bP_g^n \\
P_g &= \rho_g R T_g \sum_{i=1}^{N_g} \frac{Y_i}{M_i} \\
e_g &= \sum_{i=1}^{N_g} Y_i \left(h_{fi}^o + \int_{T^o}^{T_g} c_{pi}(\hat{T}_g) d\hat{T}_g \right) - R T_g \sum_{i=1}^{N_g} \frac{Y_i}{M_i} \\
e_s &= \sum_{i=1}^{N_s} Y_i \left(h_{fi}^o + \int_{T^o}^{T_s} c_{pi}(\hat{T}_s) d\hat{T}_s \right) \\
V &= V_g + V_s
\end{aligned}
$$

Y_i estimated from minimization of Gibbs free energy

Variables

$e_g, V_g, T_g, P_g, \rho_g,$

$e_s, V_s, T_s,$

V, Y_i, r

Constants

$\rho_s, A, h, T_w, \sigma, \alpha, \epsilon, m_p, a, b, n, R, M_i$

Piston Energy calculation

Knowledge of $P_g(t)$ and $V(t)$ allows calcuation of work done by pyrotechnic material:

$$W(t) = \int_0^t P_g(\hat{t}) \frac{dV(\hat{t})}{d\hat{t}} d\hat{t}$$

Current Solution Approach

- use NASA Lewis CEC code to estimate equilibrium products via minimization of Gibbs free energy
- solve coupled ODE–algebraic system
  - numerical integration of ODE
  - SLNL-CHEMKIN package to determine gas energy
- calculate work done by gas
- compare peak pressure and work with observations

Future

- wall friction
- shear pin effects
- spatial resolution
- grain size effects
- burn rate experiments
- detailed chemistry
- stochastic effects

Conclusions

- literature search shows little published articles on modeling of pyrotechnically driven actuators
- insufficient constitutive data for full-scale model
- simple deterministic model appears useful to better guide design
- assumptions of simple model preclude capturing of many observed phenomena
- results from simple model should be first evaluated then decisions made regarding where to make improvements

APPENDIX A - List of Participants

Aerojet - ASRM Division
Chris J. Zimmerman
Bldg. 1960, Department 7210
P.O. Box 1270
Orangeville, CA 95662-1270
(916) 355-2907 (FAX) 355-6048

Aerojet - ASRM Division
Leigh W. McDaniel
Bldg. 1960, Department 7210
P.O. Box 1270
Orangeville, CA 95662-1270
(916) 355-4849 (FAX) 355-6048

Aerojet Propulsion Division
Gerald E. Litzinger
Dept. 5236 - Building 2019A
P.O. Box 13222
Sacramento, CA 95813-6000
(916) 355-4794 (FAX) 355-6543

The Aerospace Corporation
James Gageby
MS M4/907
2350 E. El Segondo Blvd.
El Segondo, CA 90245
(310) 336-7227 (FAX) 336-1474

The Aerospace Corporation
Selma Goldstein
MS M4-907
P.O. Box 92957
Los Angeles, CA 90009-2957
(310) 336-5969 (FAX) 336-1474

Allied Signal Aerospace Co.
James L. Hendrix
Dept. 343-3 MS FK41
P.O. Box 419159
Kansas City, MO 64141-6159
(816) 997-3483 (FAX) 997-4113

Allied Signal Aerospace Co.
Allan G. Bennett
Dept. 343 MS MY40
P.O. Box 419159
Kansas City, MO 64141-6159
(816) 997-3615 (FAX) 997-5649

Allied Signal Aerospace Co.
Larry Sheets
K.C. Division, D/855, FN40
P.O. Box 419159
Kansas City, MO 64141-6159
(816) 997-4892 (FAX) 997-2411

Analex Corporation
Floyd Smith
3001 Aerospace Parkway
Brookpark, OH 44142-1003
(216) 977-0201 (FAX) 977-0200

Analex Corporation
Paul Steffes
3001 Aerospace Parkway
Brookpark, OH 44142-1003
(216) 977-0123 (FAX) 977-0200

Analex Corporation
Dan Trowbridge
3001 Aerospace Parkway
Brookpark, OH 44142-1003
(216) 977-0204 (FAX) 977-0200

Boeing Aerospace & Electronics
Jim Fitzpatrick
Code EP5
2201 NASA Road One
Houston, TX 77058
(713) 483-9050 (FAX) 483-3096

Boeing Defense & Space Group - Space Systems
Mark K. Kosai
M/S 8C-09
P.O. Box 3999
Seattle, WA 98124
(206) 773-2048 (FAX) 773-8197

EG&G Mound Applied Technologies
Thomas M. Beckman
P.O. Box 3000
Miamisburg, OH 45343-0987
(513) 865-4551 (FAX) 865-3491

EG&G Mound Applied Techologies
Alan C. Munger
P.O. Box 3000
Miamisburg, OH 45343-0987
(513) 865-3544 (FAX) 865-3491

EG&G Mound Applied Techologies
Daniel Kramer (COS-3)
P.O. Box 3000
Miamisburg, OH 45343-0987
(513) 865-3558 (FAX) 865-3680

EG&G Mound Applied Technologies
Ed Spangler
P.O. Box 3000
Miamisburg, OH 45343-3000
(513) 865-3528 (FAX) 865-3491

Energetic Materials Technology
Peter Ostrowski
P.O. Box 6931
Alexandria, VA 22306-0931
(703) 780-5854 (FAX) 780-4955

Ensign Bickford Aerospace Co.
Arthur D. Rhea
640 Hopmeadow St.
P.O. Box 427
Simsbury, CT 06070
(203) 843-2360 (FAX) 843-2621

Ensign Bickford Aerospace Co.
David W. Ewick
P.O. Box 427
Simsbury, CT 06070
(203) 843-2425 (FAX) 843-2621

Ensign Bickford Aerospace Co.
Stephen R. McComb
640 Hopmeadow St.
P.O. Box 427
Simsbury, CT 06070
(203) 843-2873 (FAX) 843-2621

General Dynamics Space System Division
Reuben Gilmore
Mail Zone 21-8550
P.O. Box 85990
San Diego, CA 92186-5990
(619) 547-7067 (FAX) 974-4000

Hercules Aerospace
David A. Cole, P.E.
P.O. Box 210
Rocket Center, WV 26726
(304) 726-5489 (FAX) 726-4730

Hercules Inc.
Pat McAllister
M/S N1EA1
P.O. Box 98
Magna, UT 84044
(801) 251-6192 (FAX) 251-6676

Hi-Shear Technology Corp.
Harold Karp
24225 Garnier Street
Torrance, CA 90509-5323
(310) 784-7853 (FAX) 325-5354

Hi-Shear Technology Corp.
Gregory G. Krisilas
24225 Garnier Street
Torrance, CA 90509-5323
(310) 784-7828 (FAX) 325-5354

Hi-Shear Technology Corp.
Jerry D. Callaghan
24225 Garnier Street
Torrance, CA 90509-5323
(310) 784-2100 (FAX) 325-5354

Hi-Shear Technology Corp.
Scott Tindol
24225 Garnier Street
Torrance, CA 90509-5323
(310) 784-7842 (FAX) 325-5354

Hughes Aircraft Company
Space & Communications Group
Jack Heifferon
Building S64 - MS B403
P.O. Box 92919
Los Angeles, CA 90009
(310) 364-7513 (FAX) 322-9164

Hughes Aircraft Company
EDSG - Initiation Lasers
M. J. (Mike) Weiner
Bldg. E-1, M/S B118
P.O. Box 902
El Segondo, CA 90245-0902
(310) 616-3985 (FAX) 616-4468

Jet Propulsion Laboratory
Anthony Agajanian
MS 158-224
4800 Oak Grove Drive
Pasadena, CA 91109
(818) 354-9339 (FAX) 393-4860

Laser Diode Inc.
Gerard Henein
1130 Somerset St.
New Brunswick, NJ 08901
(908) 249-7000 ext 210 (FAX) 249-9165

Laser Diode Inc.
Steve Klunk
1130 Somerset St.
New Brunswick, NJ 08901
(908) 249-7000 ext 218 (FAX) 249-9165

Laser Diode Inc.
Jim Pooladdej
1130 Somerset St.
New Brunswick, NJ 08901
(908) 249-7000 ext 219 (FAX) 249-0027

Lockheed Corporation
Les J. Wynn
Mail Code C50
2400 NASA Road One
Houston, TX 77058-3799
(713) 333-7795 (FAX) 333-7541

Lockheed Engineering & Sciences Co.
James L. Shaffner
Mail Code C50
2400 NASA Road 1
Houston, TX 77058-3799
(713) 333-7013 (FAX) 333-7541

Lockheed Engineering & Sciences Co.
R. E. Gibson
Mail Code C50
2400 NASA Road 1
Houston, TX 77058-3799
(713) 333-6041 (FAX) 333-7541

Lockheed Missiles & Space Co.
Richard G. Hallmark
Org. 8P-01, Bldg. 154
1111 Lockheed Way
Sunnyvale, CA 94089-3504
(408) 742-0428 (FAX) 756-3746

Los Alamos National Laboratory
James E. Kennedy
MS - P950
Los Alamos, NM 87545
(505) 667-1468 (FAX)667-6301

McDonnell Douglas Electronic Systems Co.
Edward M. Tribula
MS 111-1182
P.O. Box 516
St. Louis, MO 63166-0516
(314) 232-1266 (FAX) 777-6408

McDonnell Douglas Electronic Systems Co.
William L. Floyd
M.S. 21-2D
5301 Bolsa Ave.
Huntington Beach, CA 92647
(714) 896-1454 (FAX) 896-6959

McDonnell Douglas Electronic Systems Co. - L&ES
Dale F. Waldo
Dept. 44A0 MS 111-1182
P O Box 516
St. Louis, MO 63166
(314) 233-1515 (FAX) 777-6408

McDonnell Douglas Electronic Systems Co. - L&ES
Barb A. Soltz
M/S 111-1182
P O Box 516
St. Louis, MO 63166-0516
(314) 232-1515 (FAX) 777-6408

McDonnell Douglas Missile Systems Co.
David R. Sumpter
Mail Code 3065660
P O Box 516
St. Louis, MO 63166-0516
(314) 234-3900 (FAX) 777-2639

McDonnell Douglas Space Systems Co.
Ian Whalley
Mail Code A3-P550/11-1
5301 Bolsa Ave.
Huntington Beach, CA 92647
(714) 896-6491 (FAX) 896-1106

National Aeronautics and Space Administration
Daniel R. Mulville
Director, Technical Standards Division
Code QE
Washington, DC 20546
(202) 453-8742 (FAX) 755-0901

National Aeronautics and Space Administration
Norman R. Schulze
Code QE
Washington, DC 20546
(202) 358-0537 (FAX) 358-2777

NASA Johnson Space Center
Barry C. Wittschen
Code EP5
2201 NASA Road One
Houston, TX 77058
(713) 483-9042 (FAX) 244-5585

NASA Johnson Space Center
Henry O. Pohl
Director of Engineering
Code EA
2201 NASA Road One
Houston, TX 77058
(713) 483-93971

NASA Johnson Space Center
Scott Hacker
Code EP5
2201 NASA Road One
Houston, TX 77058
(713) 483-9042 (FAX) 483-3096

NASA Johnson Space Center
Maureen L. Bibeault
Code EP63
2201 NASA Road One
Houston, TX 77058
(713) 483-8799 (FAX) 483-1340

NASA Johnson Space Center
James Johnson
Code EP5
2201 NASA Road One
Houston, TX 77058
(713) 483-9042 (FAX) 483-3096

NASA Johnson Space Center
Carl W. Hohmann
Code EP5
2201 NASA Road One
Houston, TX 77058
(713) 483-4533 (FAX) 483-3096

NASA Johnson Space Center
Christopher Brown
Code EP5
2201 NASA Road One
Houston, TX 77058
(713) 483-9049 (FAX) 483-3096

NASA Johnson Space Center
William Hoffman
Code EP5
2201 NASA Road One
Houston, TX 77058
(713) 483-9056 (FAX) 483-3096

NASA Johnson Space Center
George W. Bulcken
SRM&QA/Loral
P.O. Box 58128
Houston, TX 77525-8128
(713) 355-2469 (FAX) 335-2348

NASA Johnson Space Center
Kenneth I. Poast
Code EP6
2101 NASA Road One
Houston, TX 77058
(713) 483-4514 (FAX) 483-1340

NASA Johnson Space Center
Keith E. Van Tassel
Code EP5
2201 NASA Road One
Houston, TX 77058
(713) 483-9053 (FAX) 483-3096

NASA Johnson Space Center
Darin N. McKinnis
Code EP5
2201 NASA Road One
Houston, TX 77058
(713) 483-9052 (FAX) 483-3096

NASA Johnson Space Center
Jay Wright
Code ND25
2201 NASA Road One
Houston, TX 77058
(713) 483-2949 (FAX) 483-2675

NASA Johnson Space Center
Ray Shearer
SRM&QA/Loral
P.O. Box 58128
Houston, TX 77525-8128
(713) 355-2499 (FAX) 335-2361

NASA Kennedy Space Center
Al Parrish
Code TV
MS D-23
Kennedy Space Center, FL 32899
(407) 861-3653 (FAX) 867-2167

NASA Langley Research Center
Larry Bement
Code 433
Hampton, VA 23665-5225
(804) 864-7084 (FAX) 864-7009

NASA Marshall Space Flight Center
Joe B. Davis
Code ED53
Marshall Space Flight Center, AL 35812
(205) 544-7019 (FAX) 544-8110

NASA Stennis Space Center
Wendy Holladay
Building 1100
Code FA10
Stennis Space Center, MS 39529-6000
(601) 688-1927 (FAX) 688-1485

NASA Stennis Space Center
William W. St. Cyr
Code HA20
Building 1100
Stennis Space Center, MS 39529-6000
(601) 688-1134 (FAX) 688-1925

NASA Wallops Flight Facility
John Hickman
Building N-159
Wallops Flight Facility
Wallops Island, VA 23337
(804) 824-2374 (FAX) 824-1518

Naval Air Warfare Center
Henry J. John, Jr.
Weapons Division (Code 3213)
China Lake, CA 93555-6001
(619) 939-7528 (FAX) 939-7226

Naval Air Warfare Center
Imelda Nee
Code 3293
China Lake, CA 93555-6001
(619) 939-7766 (FAX) 939-7562

Naval Air Warfare Center
Homer O. Valle
Weapons Division (Code 3030)
Range Safety (P4008)
Pt. Mugu, CA 93042
(805) 989-7142/7607 (FAX) 989-7743

Naval Research Laboratory
Charles Morgan
4555 Overlook Ave. S.W.
Washington, DC 20375-5000
(202) 767-6530 (FAX) 767-4633

Naval Research Laboratory
Mark Fratta
MS 8112
4555 Overlook Ave. S.W.
Washington, DC 20375-5000
(202) 594-7330 (FAX) 767-4633

Naval Surface Warfare Center
Gerald Laib
Code R12 Building 30-118
10901 New Hampshire Blvd.
Silver Springs, MD 20903-5000
(301) 394-2324 (FAX) 394-4826

Naval Surface Warfare Center
Indian Head Division - Code 5220
Jose M. Gutierrez
101 Strauss Ave.
Indian Head, MD 20640-5035
(301) 743-4447 (FAX) 743-4881

Naval Surface Warfare Center
Indian Head Division - Code 5310
Craig A. Pfleeger
101 Strauss Ave.
Indian Head, MD 20640-5035
(301) 743-4217 (FAX) 743-4881

Naval Surface Warfare Center
Indian Head Division - Code 5240E
Tom Blachowski
101 Strauss Ave.
Indian Head, MD 20640-5035
(301) 743-4243 (FAX) 743-4881

Naval Surface Warfare Center
Indian Head Division - Code 5220C
Philip A. Renn
101 Strauss Ave.
Indian Head, MD 20640-5035
(301) 743-4946 (FAX) 743-4881

Northrop Corp.
Ed Drumheller
E110/89
One Northrop Ave.
Hawthorne, CA 90260
(310) 332-0886 (FAX) 332-3066

Pacific Scientific Corp.
Energy Systems Division
Bob LaFrance
7073 West Willis Road, Box 5002
Chandler, AZ 85226-5111
(602) 796-1100 (FAX) 796-0754

Pacific Scientific Corp.
Energy Systems Division
Donald J. Behrens
7073 West Willis Road
Box 5002
Chandler, AZ 85226-5111
(602) 796-1100 (FAX) 796-0754

Quantic Industries, Inc.
Kenneth E. Willis
900 Commercial Street
San Carlos, CA 94070-4084
(415) 637-3074 (FAX) 592-4669

Sandia National Laboratories
Steven M. Harris
Organization 2513
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-0949 (FAX) 844-5924

Sandia National Laboratories
William Kass
Division 2234
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-6844 (FAX) 844-8168

Sandia National Laboratories
Jere G. Harlan
Organization 2512
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-4401 (FAX) 844-4709

Sandia National Laboratories
Richard D. Wickstrom
Dept 2514
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 845-8019 (FAX) 844-5924

Sandia National Laboratories
John A. Merson
Division 2512
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-2756 (FAX) 844-4709

Sandia National Laboratories
Weng Chow
Division 2235
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-9088 (FAX) 844-8168

Sandia National Laboratories
William W. Tarbell
Organization 2514
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-7690 (FAX) 844-0820

Sandia National Laboratories
Ron L. Hospelhorn
Department 2346
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 845-9113 (FAX) 844-1214

Sandia National Laboratories
Robert E. Setchell
Department 5166
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-3847 (FAX) 844-7431

Sandia National Laboratories
Robert W. Bickes Jr.
Organization 2513
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-0423 (FAX) 844-5924

Sandia National Laboratories
Paul V. Dressendorfer
Dept. 2235
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-5373 (FAX) 844-8168

Sandia National Laboratories
Dennis E. Mitchell
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 845-8294 (FAX) 844-5924

Sandia National Laboratories
Kent Meeks
Department 5166
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-1040 (FAX) 844-7431

Sandia National Laboratories
Manny Vigil
Dept. 2513
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-4660 (FAX) 844-4709

Sandia National Laboratories
Kevin J. Fleming
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-8510 (FAX) 844-0820

Sandia National Laboratories
John D. Matthews
Organization 2514
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 845-8763 (FAX) 844-5924

Sandia National Laboratories
J. F. Jones
Department 2574
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-8656 (FAX) 844-1214

Sandia National Laboratories
F. Jim Salas
Organization 2512
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-3265 (FAX) 844-4709

Santa Barbara Research Center
Hughes Aircraft Company
Jim Aloise
75 Coromar Drive B30/12
Goleta, CA 93117
(805) 562-4910 (FAX) 562-4024

Santa Barbara Research Center
Hughes Aircraft Company
Larry Snarr
75 Coromar Drive B30/12
Goleta, CA 93117
(805) 562-4002 (FAX) 562-4024

Santa Barbara Research Center
Hughes Aircraft Company
Roman Gonzales
75 Coromar Drive B30/12
Goleta, CA 93117
(805) 562-7705 (FAX) 562-7882

Schimmel Company
Morry L. Schimmel
8127 Amherst Avenue
St. Louis, MO 63130
(314) 863-7725 (FAX) 727-8107

Scot Inc.
Jed Potter
25341 Via Oriol
Valencia, CA 91355
(805) 259-4426 (FAX) 259-4426

Scot Inc.
John Cobbett
2525 Curtiss St.
Downers Grove, IL 60515
(708) 969-0620 (FAX) 969-4719

Special Devices, Inc.
Robert Ritchie
16830 W. Placerita Canyon Rd.
Newhall, CA 91321
(805) 259-0753 (FAX) 254-4721

Special Devices, Inc.
William J. Sipes
16830 W. Placerita Canyon Rd.
Newhall, CA 91321
(805) 259-0753 (FAX) 254-4721

Spectra Diode Laboratories
Richard Craig
80 Rose Orchard Way
San Jose, CA 95134
(408) 943-9411 (FAX) 943-1070

Teledyne McCormick Selph
Robert W. Ingnam
3601 Union Road
P.O. Box 6
Hollister, CA 95024-0006
(408) 637-3731 ext 225 (FAX) 637-5494

TRW Ballistic Missile Division
Lien C. Yang
M/S SB2/1021
P.O. Box 1310
San Bernardino, CA 92402-1310
(714) 384-7309 (FAX) 384-7273

Unidynamics
Paul Redd
102 S. Litchfield Road
Goodyear, AZ 85338
(602) 932-8574 (FAX) 932-8949

United Technologies/USBI
C. F. Webster
Building 188
P.O. Box 1900
Huntsville, AL 35807
(205) 721-2342 (FAX) 721-2263

Universal Propulsion Co., Inc. (UPCO)
Tom Wergen
25401 North Central Ave.
Phoenix, AZ 85027-7837
(602) 869-8067 (FAX) 869-8176

University of Notre Dame
Joseph M. Powers
Aerospace & Mechanical Engineering
365 Fitzpatrick Hall
Notre Dame, IN 46556-5637
(219) 239-5978 (FAX) 239-8341

University of Notre Dame
Keith A. Gonthier
Aerospace & Mechanical Engineering
365 Fitzpatrick Hall
Notre Dame, IN 46556-5637
(219) 239-5978 (FAX) 239-8341

U. S. Air Force
Aeronautical Systems Division
Lawrence Rogers
ASD/ENECC Building 126, Bay 222
Wright Patterson AFB, OH 45433-6503
(513) 255-6920 (FAX) 476-7572

U. S. Air Force
Stephan Tipton
OC-ALC/LSES
Tinker AFB, OK 73145
(405) 736-7444 (FAX) 736-3714

U. S. Air Force/30th Space Wing
Mark Gotfraind
30 SPW/SESX
Vandenberg AFB, CA 93437-6021
(805) 734-8232 ext
(FAX) 734-8232 ext

U. S. Air Force/30th Space Wing
Abe M. Takasugi
30 SPW/SESX
Vandenberg AFB, CA 93437-6021
(805) 734-8232 ext 69751
(FAX) 734-8232 ext 58030

Commander, U.S. Army
White Sands Missle Range
STEWS-NR-CE (A. Lechuga)
White Sands Missle Range, NM 88002-5137
(505) 678-4126 (FAX) 678-3795

UTC/Chemical Systems Division
K. S. Lai
P.O. Box 49028
San Jose, CA 95161-9028
(408) 776-4327 (FAX) 776-4444

Vitro Corporation
William C. Wells
Suite 300W
600 Maryland Ave., S.W.
Washington, DC 20024

Whittaker Ordnance
Michael C. Todd
2751 San Juan Road
Hollister, CA 95023

APPENDIX B - Written Questions and Answers

Question:	Response:
Dr. Lien C. Yang (TRW) Absorptive particulated doped HMX and PETN can be initiated by laser. But the threshold may degrade post environmental test, especially temperature cycling. Are there plans to perform any test?	Dr. J. A. Merson (Sandia Nat. Labs) Yes. Powder separation may be a problem. It is no different than bridgewire decoupling and therefore there are engineering solutions.
Dr. Richard Craig (Spectra Diode Labs) As you develop a standard laser diode safe and arm: 1) How do you get input from system and component manufacturers? 2) How will you distribute your concepts to the community?	Mr. Barry Wittschen (NASA/JSC) 1) The word "standard", as applied to a laser safe and arm may be a misnomer. What we are going to attempt to do is identify major criteria for system configuration, methods for implementing inhibits, methods for qualifying the S&A and acceptance test requirements. 2) The most critical application for the S&A is in flight termination systems (FTS). FTS requirements are established by the range safety organizations. The primary input will therefore develop through dialogue with the ranges and then be distributed by the ranges in the form of revisions to their own safety requirements. Additional distribution will be through future NASA and AIAA conferences.
Dr. Lien C. Yang (TRW) Is it possible to re-adopt ASI (Apollo Standard Initiator) output charge design using $TiH_2/KeLO_4$ composition for increasing the gaseous output? ASI was extensively tested in 1960's. Large performance data base exists.	Mr. Larry Bement (NASA/LaRC) No possibility exists to change the output charge in the NSI, as it is now qualified. The $TiH_2/KeLO_4$ may be some benefit for the NASA Standard Gas Generator, but the ignition and primary charge must remain $Zr/KeLO_4$.

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